Applications of Automatic Differentiation

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Multidisciplinary Optimization Branch

Aerospace Concepts and Analysis Competency

Methods Development Peer Review - Nov. 2001

Current Collaborators:

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2 NASA LaRC / AAAC / CMSB
3 Boeing Long Beach
4 NASA LaRC / AirSC / DCB
5 NASA LaRC / ASCAC / MDOB
6 NASA LaRC / AirSc / VDB

ASCoT Project (1998-2002)

(Aerospace Systems Concept to Test)

Project Vision

Physics-based modeling and simulation with sufficient speed and accuracy for validation and certification of advanced aerospace vehicle design in less than 1 year

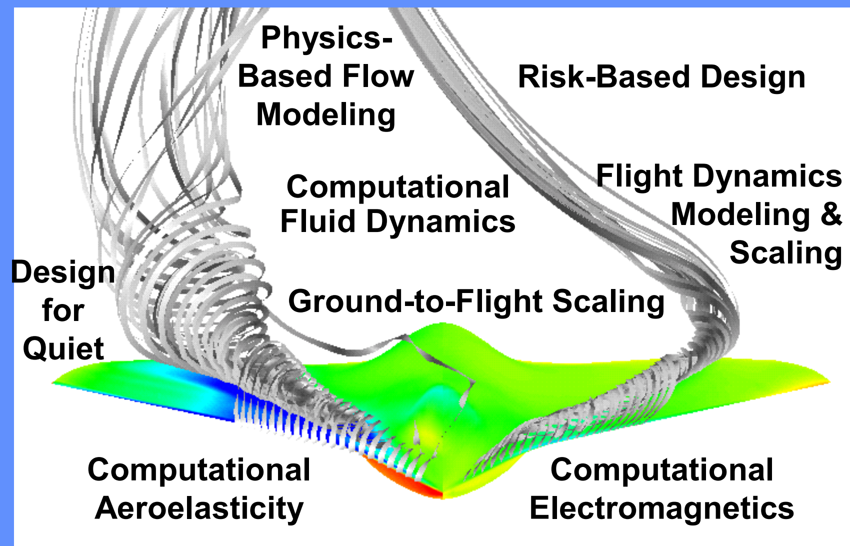
Project Goal

- **Provide next-generation analysis & design tools to increase confidence and reduce development time in aerospace vehicle designs**

Objective

- Develop **fast, accurate, and reliable** analysis and design tools via fundamental technological advances in:
  - **Physics-Based Flow Modeling**
  - Fast, Adaptive, Aerospace Tools (CFD)
  - Ground-to-Flight Scaling
  - **Time-Dependent Methods**
  - Design for Quiet
  - **Risk-Based Design**

Technology Areas



Aircraft Computational Stability & Control (S&C) Derivative Example

Benefit

- Increased Design Confidence
- Reduced Development Time

Introduction to Sensitivity Methods

Motivation / Objectives

- Accurate and consistent derivatives of disciplinary analyses are needed for optimization and uncertainty analyses
- Legacy analysis codes don't usually provide derivatives
- Respond quickly to changes in the design environment
  - Design variables, objective, and constraints
  - Algorithms, physics models, and computational paradigms
- Sensitivity methods
  - \+ physics-based flow modeling = **static S&C derivatives**
  - \+ time dependent methods = **dynamic S&C derivatives**
  - \+ optimization methods = **conventional design**
  - \+ uncertainty propagation = **robust design**
- Assess / improve the computational impact
- Transfer tools and techniques to others

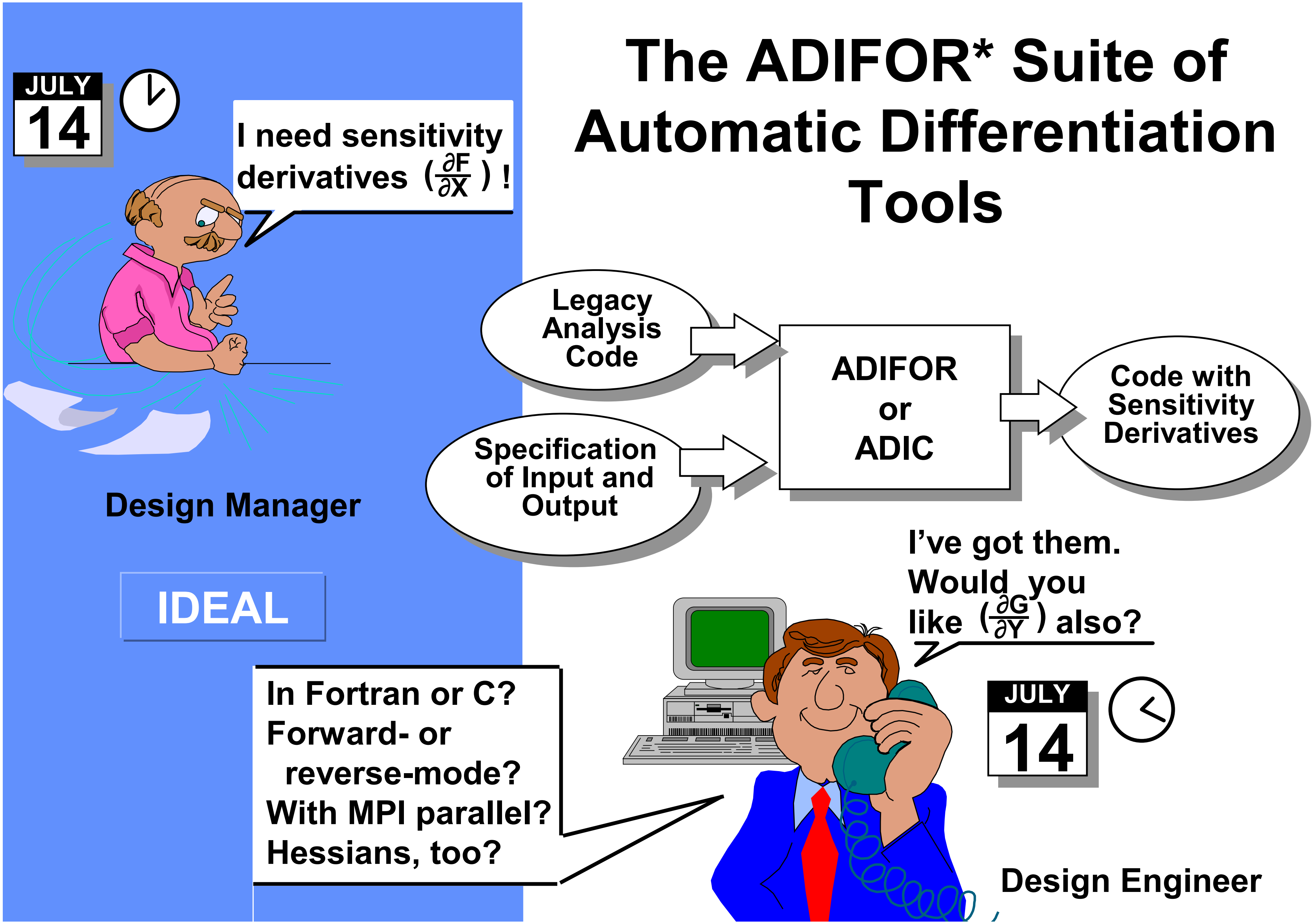
Introduction to Sensitivity Methods

Comparison of Methods

- Finite-differences (FD) (approximation, step size dependent)
- Manual differentiation (exact, tedious, prone to errors)
- Symbolic manipulators (exact, limited scope of application)
- Complex arithmetic (exact, similar to FD, can't be used if complex arithmetic is already present, no adjoint formulation)
- **Automatic Differentiation (AD) – ADIFOR**
  - Application is fast and easy for standard Fortran 77
  - Exact to machine and problem formulation precision
  - Can be computationally much faster than FD
  - Forward (direct) and reverse (adjoint) forms available
  - Rigorous verification of accuracy (not discussed here)
- Hybrid schemes (AIAA 94-4262* and AIAA 2001-2529)
  - Leverage strengths / minimize weaknesses of several methods
  - Employ disciplinary, code, and differentiation knowledge
  - Improve computational efficiency

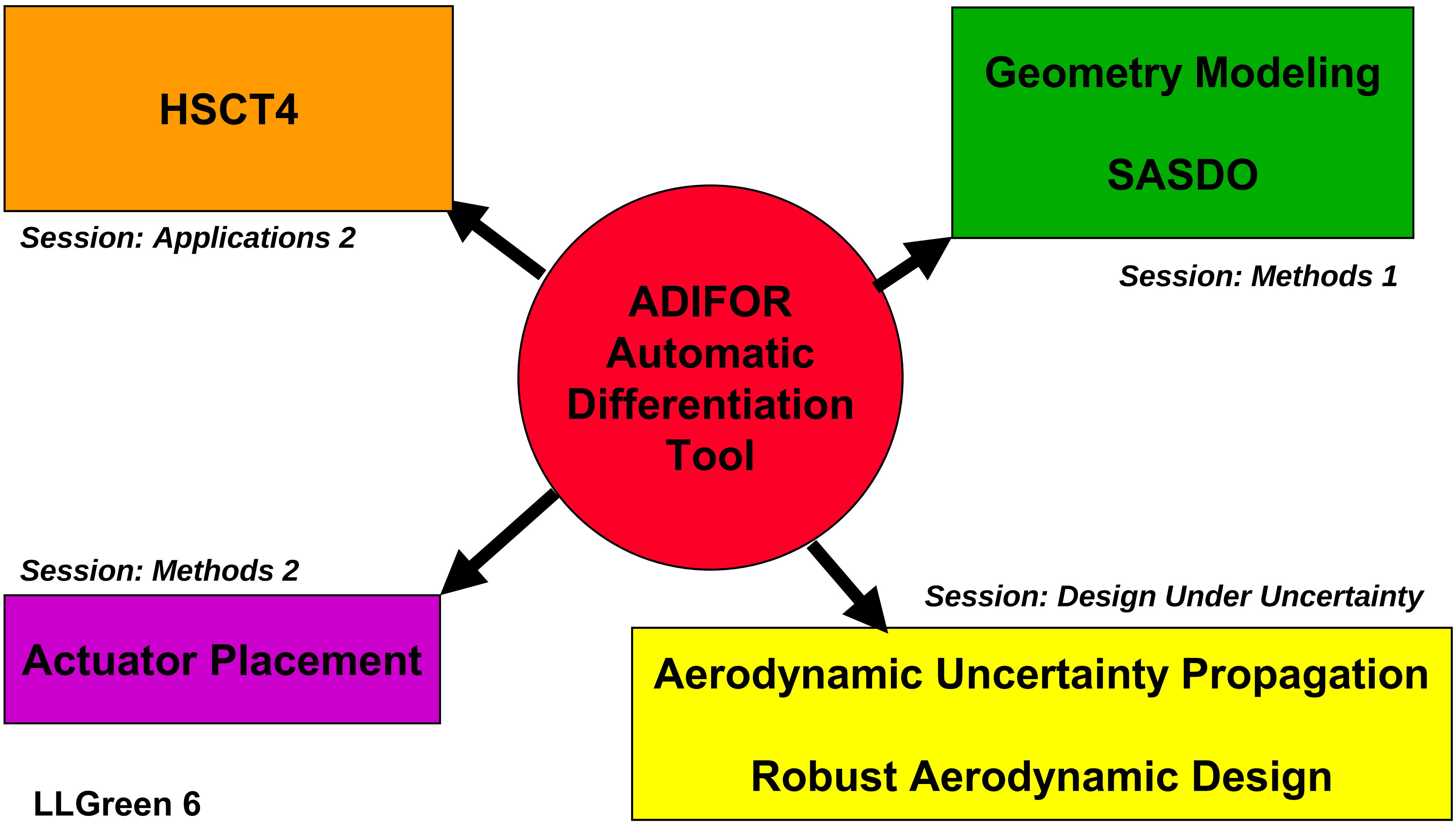
*** Also, Journal of Computational Physics, Vol. 129, p307-331, 1996**

The ADIFOR* Suite of Automatic Differentiation Tools



* Developed by Rice University and Argonne National Laboratory
Winner 1995 Wilkinson Prize for Numerical Software

ADIFOR Connections to Other MDOB Activities



PMARC

- Panel Method – Ames Research Center
- Dale Ashby, et.al. (NASA ARC)
- Time-dependent low-order potential-flow with boundary-layer correction
- Forward- and reverse-mode ADIFOR applications

CFL3D

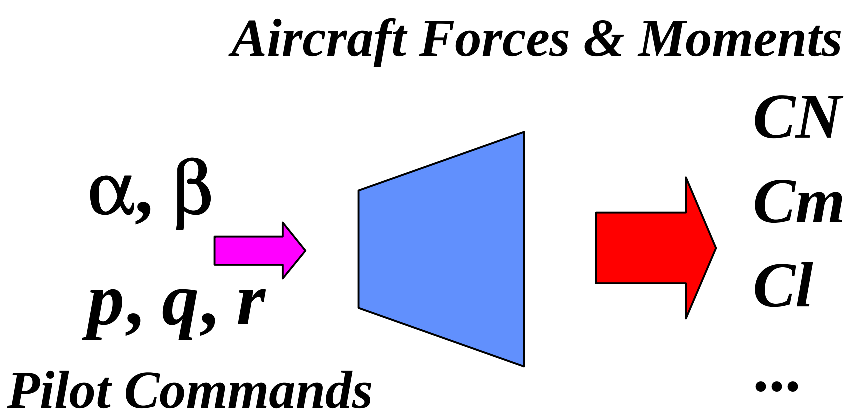
- Computational Fluids Laboratory 3-Dimensional
- Thomas, Rumsey, Biedron, etc. (NASA LaRC)
- Euler / Navier-Stokes (N-S); several turbulence models
- N-S Spalart-Allmaras (S-A) turbulent flow cases presented
- Executes on NASA Langley and Ames Silicon Graphics, Inc.(SGI) Origin 2000™ parallel computers
- Version 6 includes dynamic memory and MPI parallel execution
- Version 6+ modified for steady-state, constant rotational rate motions

Featured ADIFOR 3.0 Applications

- Computation of static / dynamic stability and control derivatives
  - 5 control variables / 6 aircraft responses
  - Forward mode AD application to PMARC and CFL3D
  - MDOB, AirSC/VDB, AirSC/DCB, and Lockheed-Martin (1998 - 2000)
- High Speed Civil Transport aerodynamic shape optimization
  - 401 design variables / 56 constraints / 1 aircraft response
  - Reverse-mode AD application to CFL3D
  - Boeing Long Beach with MDOB expertise (1999 - 2000)
- Reusable Launch Vehicle (RLV) aero-thermal shape optimization
  - 35 design variables / 6 constraints / 2 vehicle responses
  - Reverse-mode AD application to CFL3D with thermal effects
  - Boeing Long Beach with MDOB funding and expertise (2001)
- Control placement effectiveness study (time permitting)
  - 1353 placement variables / 3 aircraft responses
  - Reverse-mode AD application to PMARC
  - MDOB, AirSC/DCB, and Lockheed-Martin (1998)

Example ADIFOR Applications

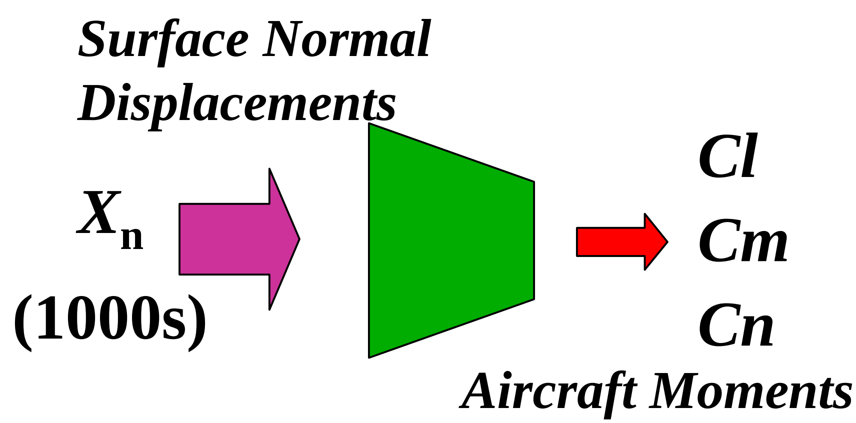
- CFL3D Euler/Navier-Stokes code
- **Forward** mode
- Chain rule of calculus
- Number of variables:
  dependent > **independent**
- Aircraft stability derivatives



AIAA 99-3136

AIAA 2000-4321

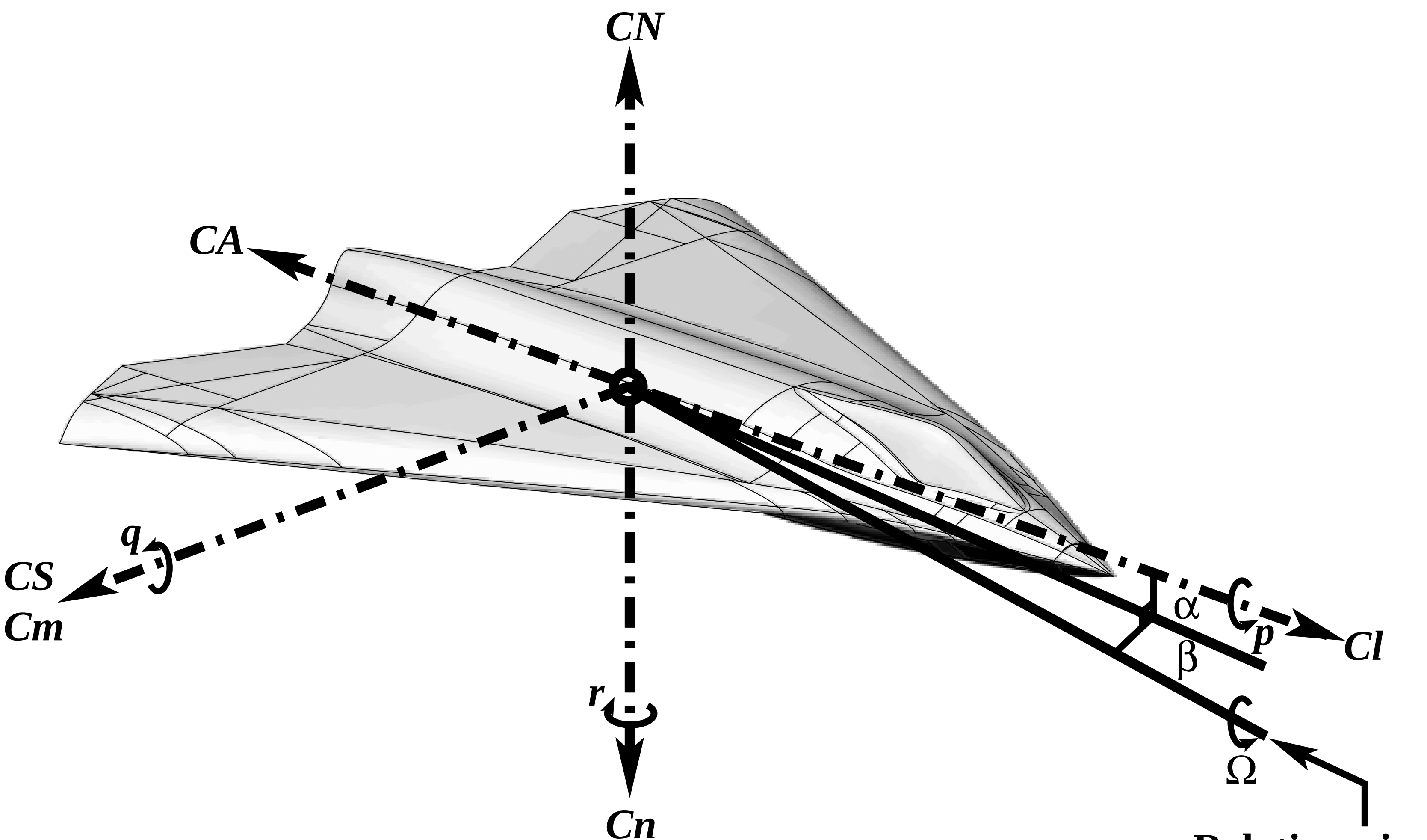
- PMARC linear aerodynamics code
- **Reverse** Mode
- Discrete adjoint formulation
- Number of variables:
  independent > **dependent**
- Control placement effectiveness



AIAA 98-4807

AIAA 2000-1560

Lockheed-Martin Innovative Control Effectors (ICE) Configuration



CFD volume grid 3 with million cells, full span
and derived linear aerodynamics surface grid

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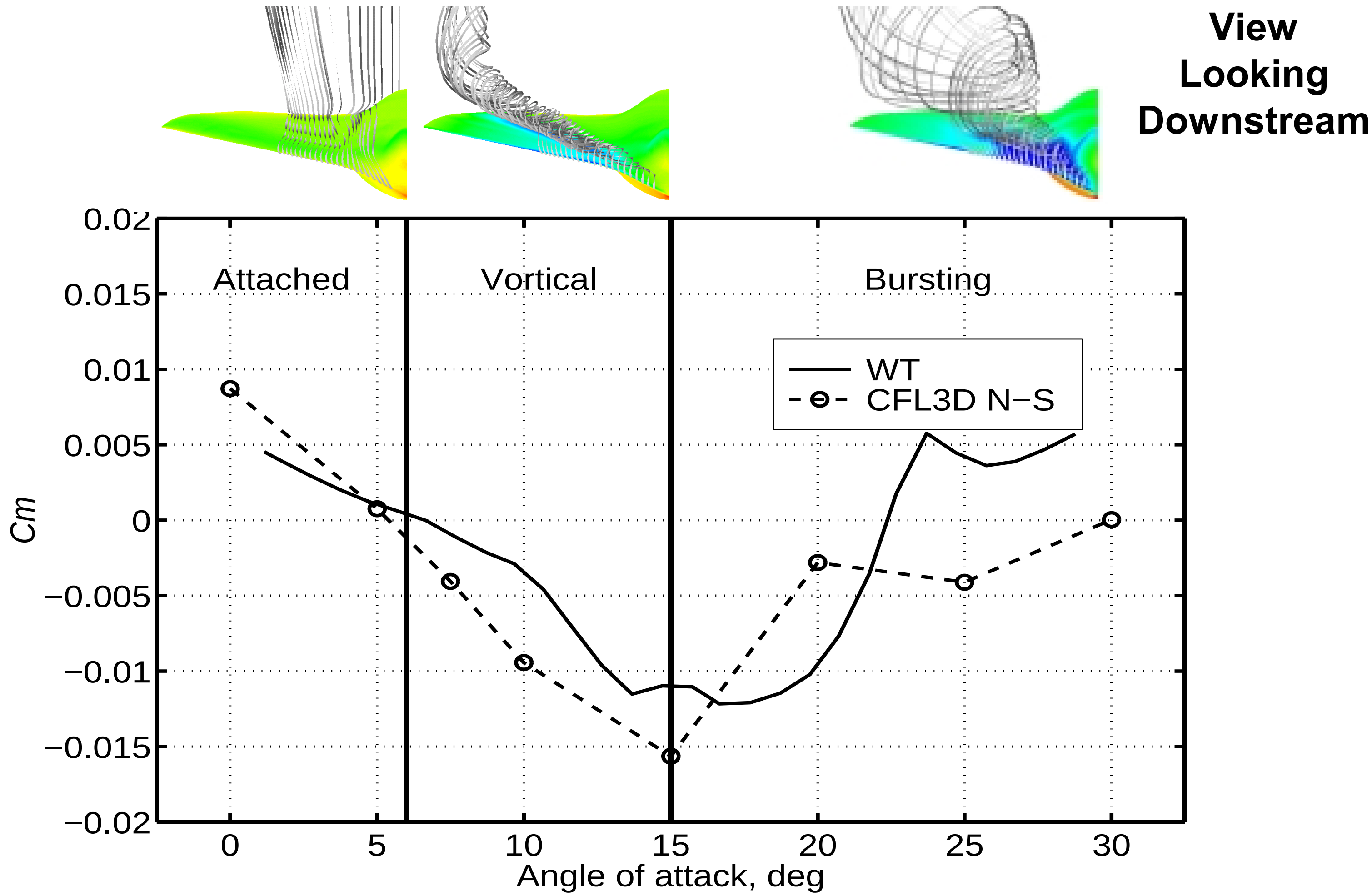
Three α ranges of flow structure

Pitching Moment, CFL3Dv6 N-S S-A, Mach = 0.6, ICE Configuration

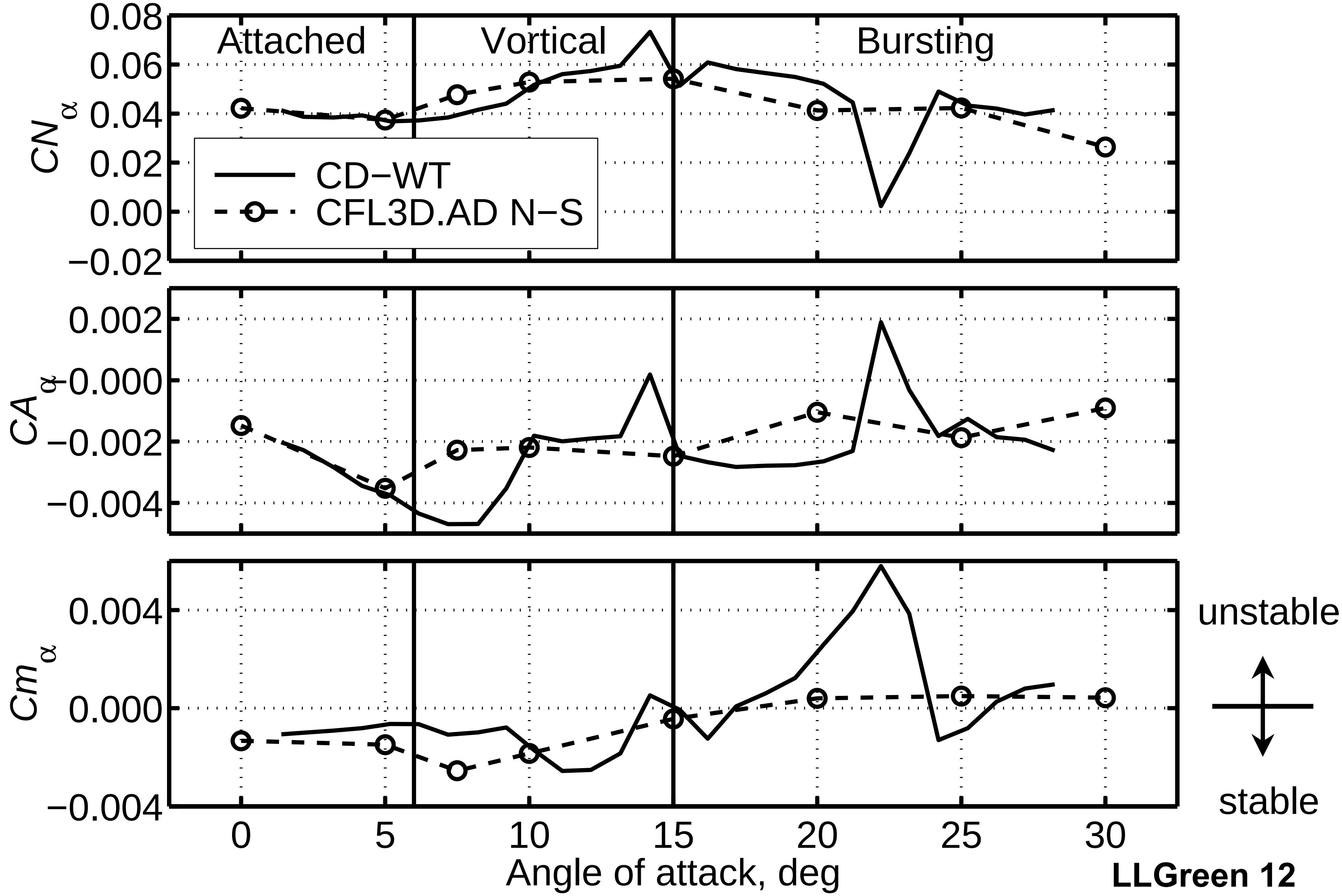


Angle of attack resolution: WT (~1 deg), CFD (~5 deg)

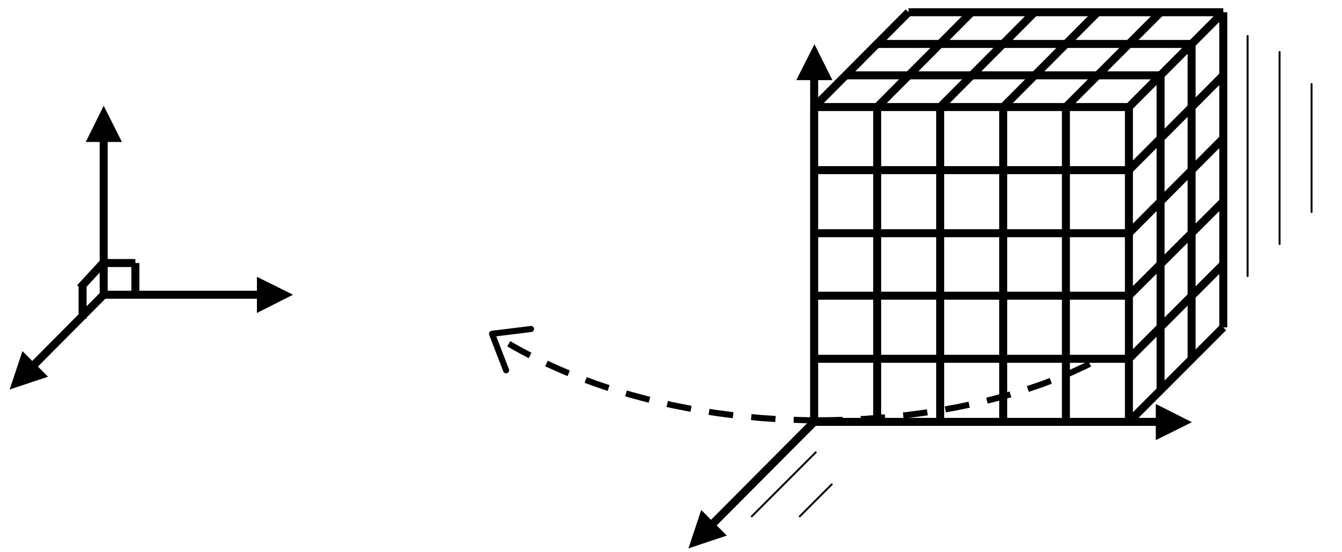
Good agreement for CN and CA with WT

Long. Static Stability (α derivatives)

CFL3Dv6.AD N-S / S-A, Mach = 0.6, ICE Configuration



Non-inertial Frame of Reference[1]



Inertial (fixed) **Non-inertial CFD grid (moving)**

- Efficient method to simulate moving CFD grids
  - Steady-state solutions of constant-rate motion
- Relatively simple to implement
  - Add source term to governing equations (induced body forces)
  - Increment boundary and initial conditions (rotational velocities)

1 Limache, A. C. and Cliff, E. M.: "Aerodynamic Sensitivity Theory for Rotary Stability Derivaties", AIAA 99-4313

Non-inertial Modifications to CFL3Dv6

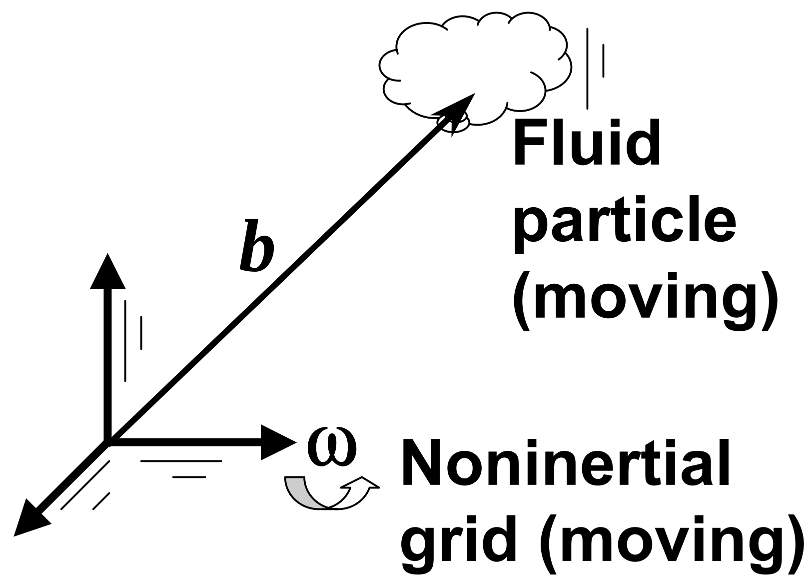
Solution update: $\frac{1}{J}\frac{\partial \boldsymbol{Q}}{\partial t} = R(\boldsymbol{Q}) + \boldsymbol{S}$ **Source Term**

Conserved variables: $\boldsymbol{Q} = \begin{bmatrix} \rho & \rho u & \rho v & \rho w & e \end{bmatrix}^T$

Source term: $\boldsymbol{S} = \frac{\rho}{J}\begin{bmatrix} 0 & \bar{\Theta}_x & \bar{\Theta}_y & \bar{\Theta}_z & \bar{\Theta}\cdot\dot{b} \end{bmatrix}^T$

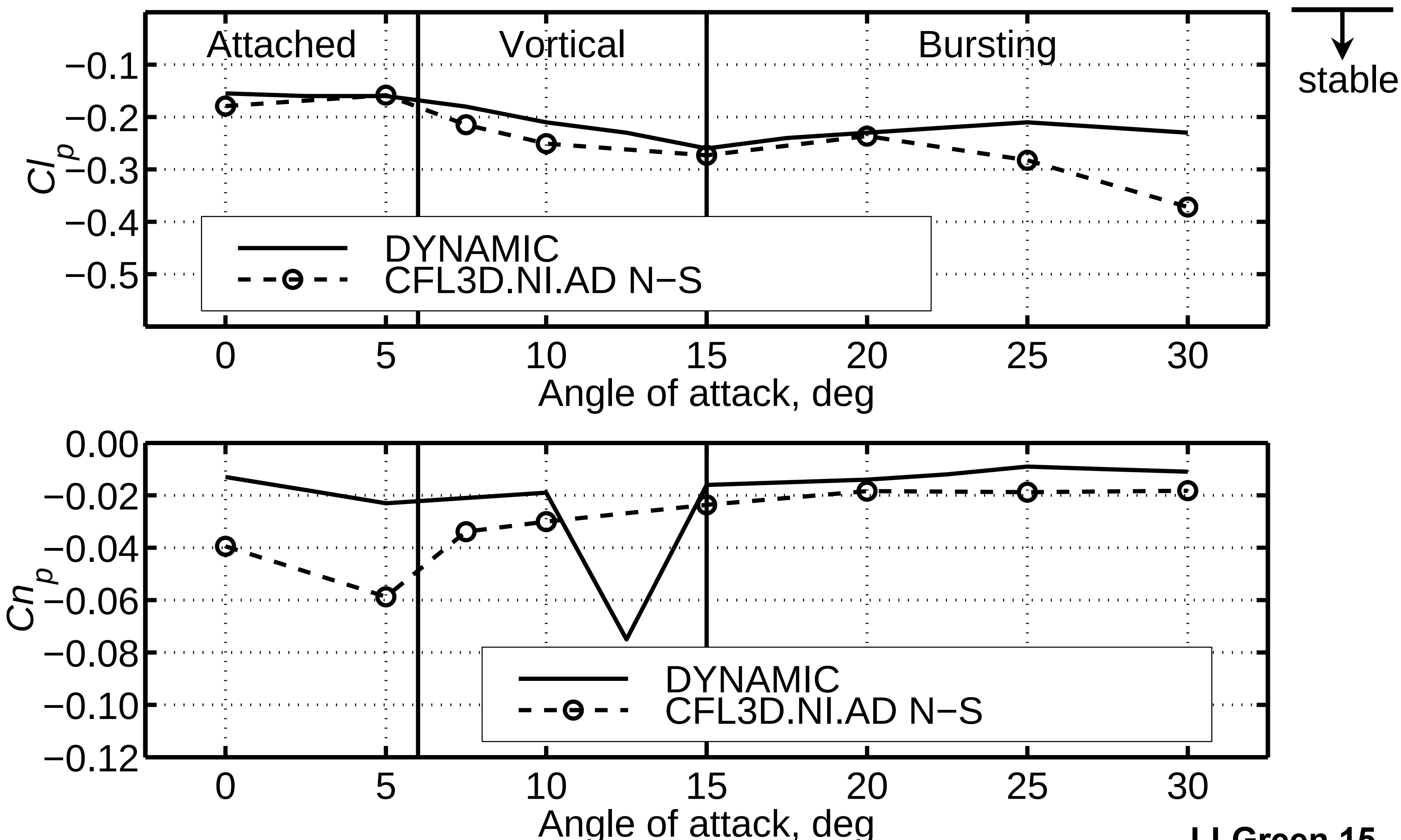
$$\frac{1}{J} = \text{Cell Volume}$$

$$\dot{b} = \begin{bmatrix} u & v & w \end{bmatrix}$$



Roll Rate Derivatives

CFL3Dv6.NI.AD N-S / S-A, Mach = 0.6, ICE Configuration



CFL3D / CFL3D.AD / CFL3D.NI.AD

Reference Data Comparison Summary, ICE Configuration

Description		Performance in Different Flow Structures		
		Attached	**Vortical Bursting**	
		0–5α	**6–15α**	**>15α**
Force and moment	($\boldsymbol{Cm}$)	Excellent	Excellent	Good
Long. Static stability	($\boldsymbol{Cm_\alpha}$)	Excellent	Excellent	Good
Lat. / Dir. Static stability	($\boldsymbol{Cl_\beta}$)	Excellent	Good	Poor*
Dynamic derivatives	($\boldsymbol{Cl_p}$)	Excellent	Excellent	Good

CFL3D.NI.AD, 0-15 deg α — **30** hr. per angle of attack case

CFL3D.NI.AD, >15 deg α — **90** hr. per angle of attack case

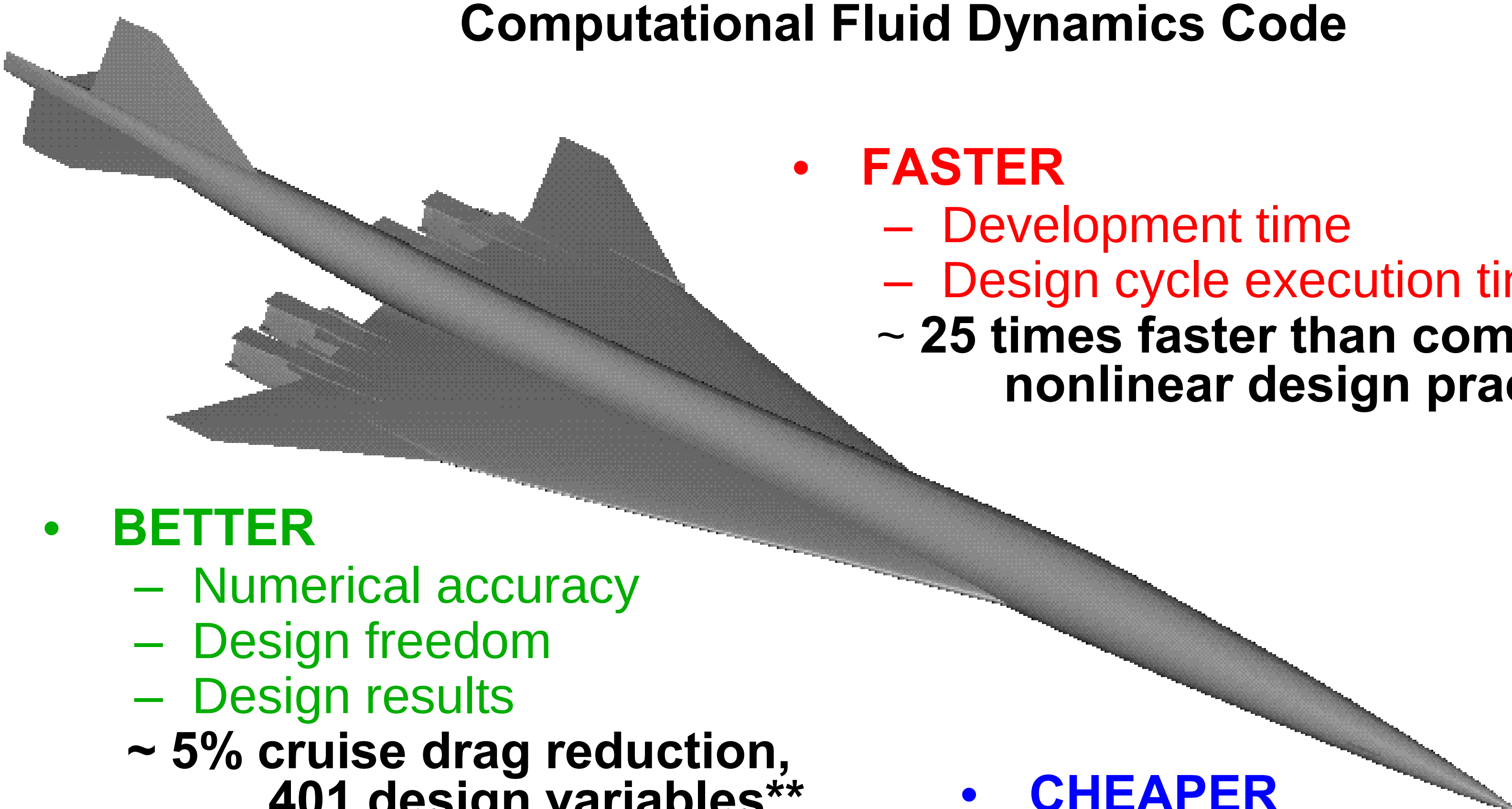
Center-difference CFL3D.NI 0-15 deg α — **44** hr. per angle of attack case

Execution on 16-processor SGI Origin 2000™ with 12 Gb RAM

* Still better than previous capability

High Speed Civil Transport Optimization

With ADJIFOR*-Generated CFL3D Adjoint Computational Fluid Dynamics Code



- **FASTER**
  - Development time
  - Design cycle execution time

  ~ 25 times faster than comparable nonlinear design practice**

- **BETTER**
  - Numerical accuracy
  - Design freedom
  - Design results

  ~ 5% cruise drag reduction, 401 design variables**

- **CHEAPER**
  - Less human resources
  - Less computer resources

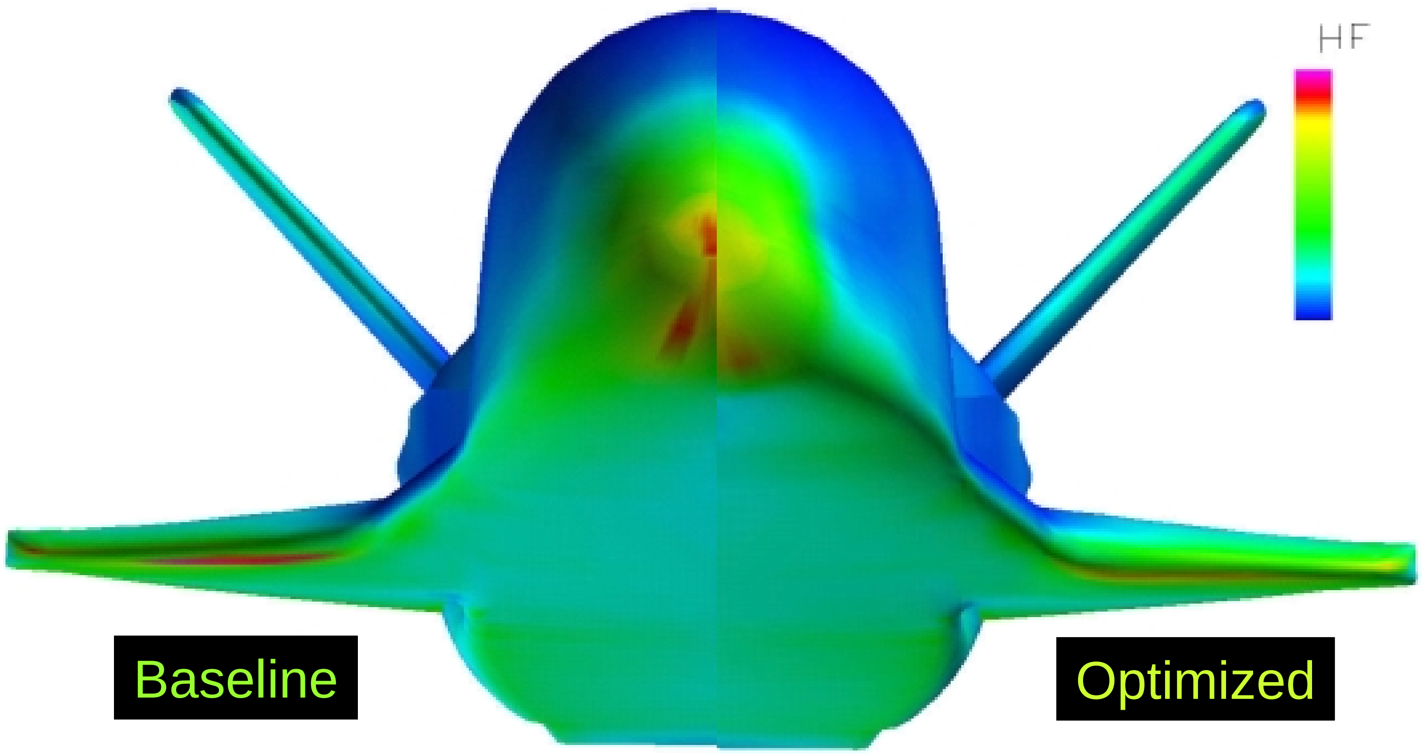
  ~ 10 times faster inviscid design cycle**

*** Developed by Rice University**

**** Initial Boeing Long Beach wing-body result**

X-37 Wing/Body Aeroheating Optimization

35 Design Variables to Minimize Maximum Heat Flux
CFL3D N-S (Menter), 38 Blocks, 0.85M Points



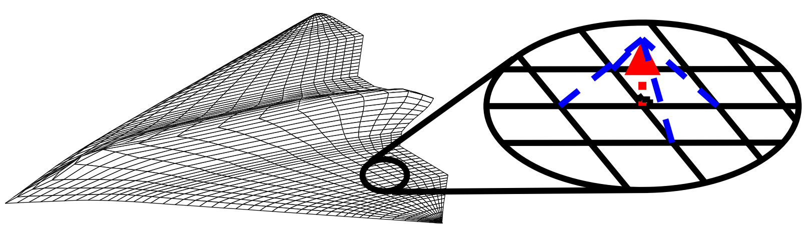
Max. Heat Flux Reduction
(7% on Forebody and 16% on Wing Leading-Edge)

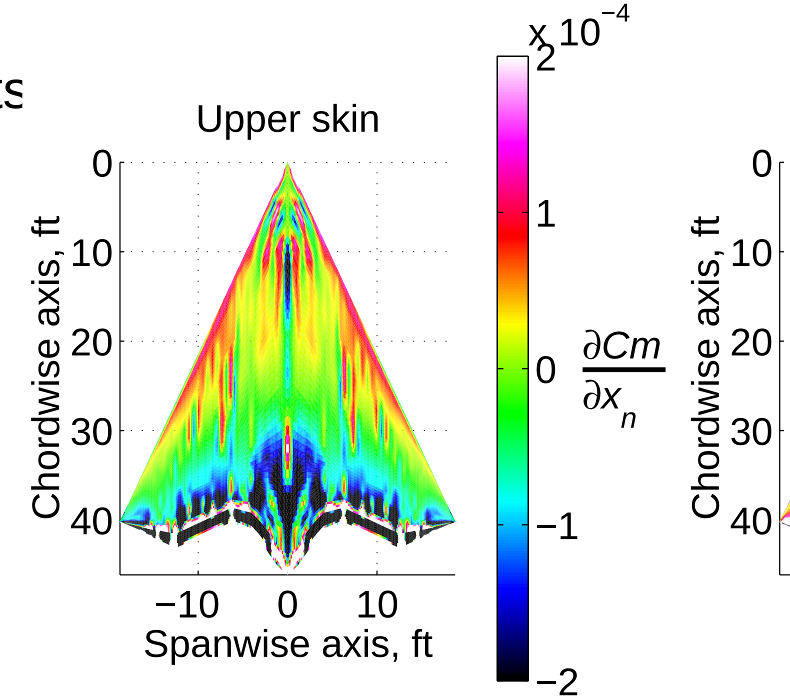
Initial Boeing Long Beach results

Control Placement Effectiveness

PMARC.AD linear aerodynamics code

- Model inflatable control effectors as bumps (outward normal displacements (*Xn*) of surface grid points)
- Control placement effectiveness is the **derivative of** pitch (***Cm***), roll (*Cl*), and yaw (*Cn*) moment coefficients **with respect to surface displacement** (***Xn***)
- Calculated for <u>each</u> of 1353 surface grid points
- Control effectiveness interpolated over the configuration surface





Part of integrated control effectors design and simulation package presented to NASA Administrator Daniel Goldin

Ongoing and Future Work

- Non-inertial modifications were implemented in the production version of CFL3Dv6; sensitivity studies of un-commanded aircraft motions (for example, F-18 E/F wing rock) are planned as cooperation between ASCOT and Abrupt Wing Stall Programs
- Second and higher derivative methods are being examined for use with S&C calculations to provide uncertain S&C data on F-16XL for use in robust control law design within ASCOT
- Second and higher derivative methods are being examined for use with aircraft robust design within ASCOT
- First-order sensitivity methods are being applied to the 2nd Generation RLV Program for uncertainty quantification and risk reduction
- Sensor / actuator placement studies for deformable nacelles are planned under the Ultra-Efficient Engine Program

Conclusions

- Automatic Differentiation enables the rapid development of next-generation analysis and design tools from legacy codes
- Automatic Differentiation provides increased confidence through automatic generation of sensitivity analyses
- Automatic Differentiation has contributed significantly to aircraft computational stability and control studies
- Recent MDOB work with ADIFOR has pioneered advanced sensitivity techniques which reduce the computational impact of sensitivity analyses
- MDOB actively seeks to transfer sensitivity tools and techniques to others
- Automatic Differentiation enables probabilistic uncertainty quantification and propagation through method of moments (Newman)

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